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14. ABSTRACT We have analyzed Millstone Hill UHF radar observations of the sub-auroral ionosphere in order to determine characteristic disturbance effects seen in both high-spatial/temporal resolution event studies and statistical analyses of over tow solar cycles of radar observations. A series of state-of-the-art radar experiments were performed which combined for the first time coherent and incoherent scatter observations [Foster and Erickson, 2001], and these provided us with a new and powerful observing technique with which to investigate electric field variability. We discovered a linear relationship between coherent scatter parameters and the driving electric field. Thus, inverting the very-high resolution coherent scatter observations provides a similar resolution analysis of the electric field. This technique was used to analyze the character of the sub-auroral electric field by Erickson et al. [2002]. In pursuing the statistically-significant perturbation electric field at sub-auroral latitudes, we developed bulk data analysis techniques which led to a characterization of sub-auroral gradients in ionospheric total electron content (TEC) [Vo and Foster, 2001], and in the large-scale ring current-driven polarization stream (SAPS) electric field [Foster and Vo, 2002] which largely has been overlooked in magnetosphere-ionosphere coupling studies in the past. In fact, the SAPS is responsible for the redistribution of thermal plasmas in the ionosphere and inner magnetosphere and is a main contributor to Space Weather effects at mid latitudes.

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Ionospheric Electric Field Response to Substorms

Abstract

We have analyzed Millstone Hill UHF radar observations of the sub-auroral ionosphere in order to determine characteristic disturbance effects seen in both high-spatial/temporal resolution event studies and statistical analyses of over two solar cycles of radar observations. A series of state-of-the-art radar experiments were performed which combined for the first time coherent and incoherent scatter observations [*Foster and Erickson*, 2001], and these provided us with a new and powerful observing technique with which to investigate electric field variability. We discovered a linear relationship between coherent scatter parameters and the driving electric field. Thus, inverting the very-high resolution coherent scatter observations provides a similar resolution analysis of the electric field. This technique was used to analyze the character of the sub-auroral electric field by *Erickson et al.* [2002]. In pursuing the statistically-significant perturbation electric field at sub-auroral latitudes, we developed bulk data analysis techniques which led to a characterization of sub-auroral gradients in ionospheric total electron content (TEC) [*Vo and Foster*, 2001], and in the large-scale ring current-driven polarization stream (SAPS) electric field [*Foster and Vo*, 2002] which largely has been overlooked in magnetosphere-ionosphere coupling studies in the past. In fact, the SAPS is responsible for the redistribution of thermal plasmas in the ionosphere and inner magnetosphere and is a main contributor to Space Weather effects at mid latitudes.

Project Description

A three-year program of radar experiments and data analysis has been undertaken at the MIT Haystack Observatory to investigate the characteristics and effects of the disturbance electric field in the sub-auroral ionosphere. The project use the MIT Millstone Hill UHF incoherent scatter radar and the 20+-year database of its observations to address both high-resolution event studies and statistical studies of ionospheric structure and dynamics during storm and substorm disturbances. MIT post-doctoral researcher received half-time support to participate in this work (Dr. H. B. Vo).

## High-Resolution Observations of Disturbance Electric Field

Detailed experiments using new radar operating modes were performed to investigate the specific properties of the mid-latitude and sub-auroral electric field during disturbed conditions. A combined coherent backscatter - incoherent scatter experiment was performed with the Millstone Hill UHF radar during strongly disturbed conditions on August 27, 1998 which provided simultaneous observations of electric field magnitude and coherent backscatter parameters on the same L shell. A carefully-designed geometry used sidelobe coherent contamination from two-stream irregularities at 110-km altitude, appearing at ranges corresponding to F-region altitudes in the main beam, in conjunction with simultaneous uncontaminated F-region observations of the $\mathbf{E} \times \mathbf{B}$ drift velocity in adjacent range gates. Three hours of such observations with 20-s temporal resolution were analyzed during varying conditions in which $|\mathbf{E}|$ varied [15, 65 mV/m]. *Foster and Erickson [2000]* found a clear linear relationship between both logarithmic coherent power and the magnitude of the coherent phase velocity with $|\mathbf{E}|$. These results are the first such observations of the relationship of coherent parameters to electric field magnitude made at 440 MHz and with the radar $\mathbf{k} \sim$ parallel to $\mathbf{V}_{ph}$.

The sensitivity of the Millstone Hill system to coherent backscatter over a wide dynamic range and the clear relationship between both coherent scatter amplitude and phase velocity and the magnitude of the electric field suggest the use of the intense coherent returns, which can be acquired with very good temporal and spatial resolution, as a monitor of both T_e and $|\mathbf{E}|$ in the perturbed E region. *Erickson et al.* [2002] used this technique to observe polarization stream electric field structure which changes in under one minute from a widespread field distributed over more than 0.6 degrees of latitude to a system of very narrow features less than 0.1 degrees latitude in extent. Multiple narrow electric field concentrations occur with overall motions of more than 0.5 degrees latitude, and intensities exceed events with more uniform fields by up to 30 dB Electric field variability is very important for addressing Joule heating effects and the energy balance between the ionized and neutral atmospheres.

Ionospheric Density Gradients at Mid Latitudes

The sub-auroral ionosphere, at the magnetic latitudes which characterize the northeastern United States, is subject to severe F-region ionospheric density structuring due to the space weather effects of magnetospheric disturbance electric fields. Communications and navigation

systems relying on trans-ionospheric propagation must be able to compensate for the effects of the sharp changes (>10x) in total electron content (TEC) associated with the ionospheric trough and storm-time disturbance effects at mid latitudes. *Vo and Foster* [2001] used the Millstone Hill inco-
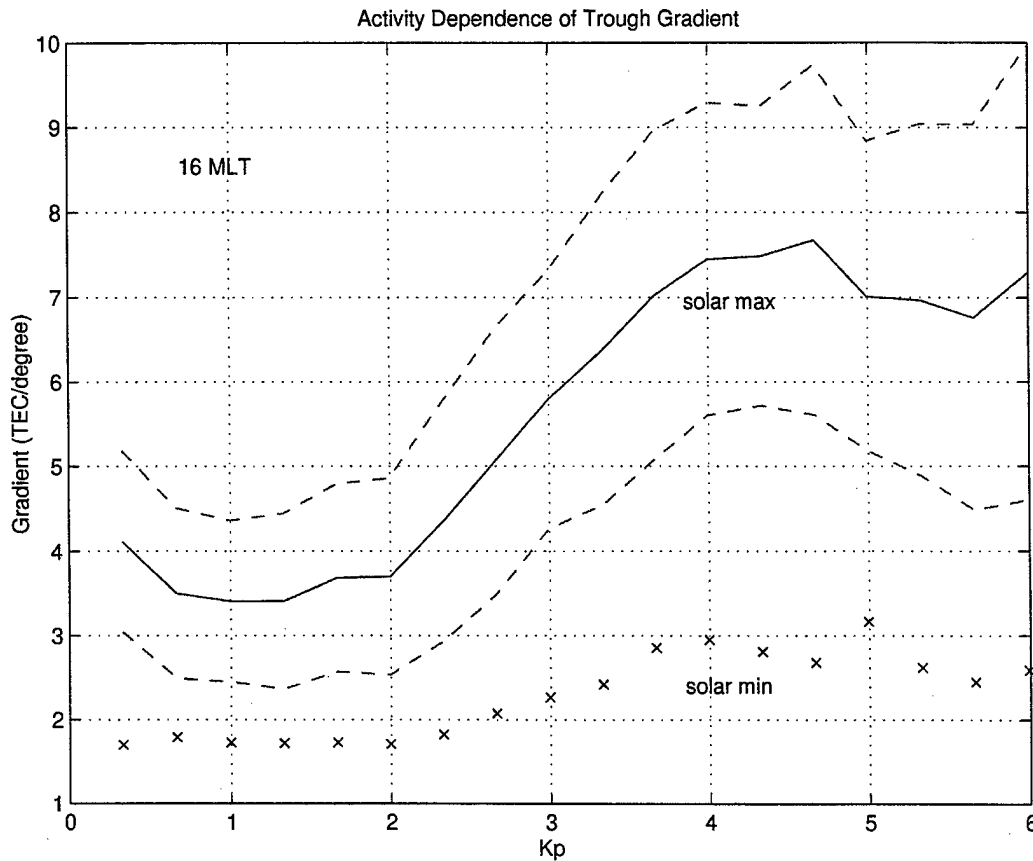
Magnetic-activity dependence of the trough TEC gradient at 16 MLT, in the local time sector of the largest gradients. The dashed contours indicate one standard deviation centered on the mean value. Solar maximum values are presented as the solid curve, with solar minimum values shown as Xs. Gradients are significantly enhanced for Kp > 3.[Vo and Foster, 2001]

herent scatter radar database to investigate the spatial extent and temporal evolution of TEC and density altitude/latitude structure at mid and sub-auroral latitudes as a function of solar cycle, local time, and level of geomagnetic activity. More than 11,000 radar elevation scans covering >20 degrees of latitude and altitudes between 150 km and 750 km were used to identify the characteristics of the density gradient near the equatorward edge of the ionospheric trough in a variety of circumstances spanning 20 years and two solar cycles. On most days the trough appears in the radar scans between 16 MLT and 20 MLT. Larger TEC gradients occur at solar maximum, when the

background TEC is higher. The steepest gradients occur in an environment of high TEC (solar max and adjacent to regions of storm-enhanced density, SED [*Foster*, 1993]), when the processes which generate the trough are strongest (high Kp). High gradient values occur in the sunlit sector with maximum values of TEC gradient (~10 TEC/deg latitude; 1 TEC unit = 10^{16} electrons m^{-2}) found in the post-noon ionosphere. Mean solar-maximum TEC gradient at 16 MLT is 3-4 TEC/deg for Kp < 2, increases linearly with Kp for Kp 2-4, and is nearly constant at a value of 7-8 TEC/deg for Kp 4-6. Storm enhanced density (SED), the bulk redistribution of *F*-region plasma by disturbance electric fields, can result in TEC > 100 over New England and TEC gradients of ~50 TEC / deg.

Average Disturbance Electric Field

Data from the Millstone Hill incoherent scatter radar taken over two solar cycles (1979-2000) were examined to determine the average characteristics of the disturbance convection electric field in the midlatitude ionosphere. Radar azimuth scans provide a regular database of ionospheric plasma convection observations spanning auroral and sub-auroral latitudes, and these scans have been examined for all local times and activity conditions. Using a standardized pattern recognition procedure, we examine the occurrence and characteristics of a persistent secondary westward convection peak which lies equatorward of the auroral two-cell convection (cf. *Yeh et al.* [1991]). *Foster and Burke* [2002] have defined this persistent feature as the sub-auroral polarization stream, SAPS. Individual scans and average patterns of plasma flow identify and characterize this latitudinally-broad and persistent SAPS feature, which spans the nightside from dusk to the early morning sector for all Kp greater than 4. Pre-midnight, the SAPS sunward convection lies equatorward of L = 4, spans 3° - 5° of latitude, and has an average peak amplitude of 1000 m/s. In the pre-dawn sector, SAPS is seen as a region of anti sunward convection equatorward of L = 3, spanning 2° - 3° of latitude, with an average peak amplitude of 400 m/s. The SAPS electric field pattern is not represented in current models of ionospheric convection.

Using our SAPS database, *Foster and Vo* [2002] have determined the mean value of the peak polarization stream ionospheric convection velocity at each MLT hour across the nightside and for Kp values between 4– and 7+. Mean flow velocity of the SAPS is 900 m/s - 1000 m/s immediately after dusk (18 MLT - 22 MLT) and decreases steadily across midnight to values near 400 m/s at dawn. Mean values of the invariant latitude of the SAPS peak are presented Figure 2. SAPS occurs near 62°Λ near dusk for Kp ~ 4, and near L = 3 (55° at midnight, and at ~52°Λ at dawn) for high

activity levels (standard deviations ~ 2° of latitude).

The sub-auroral polarization stream has considerable consequences on the dynamics and
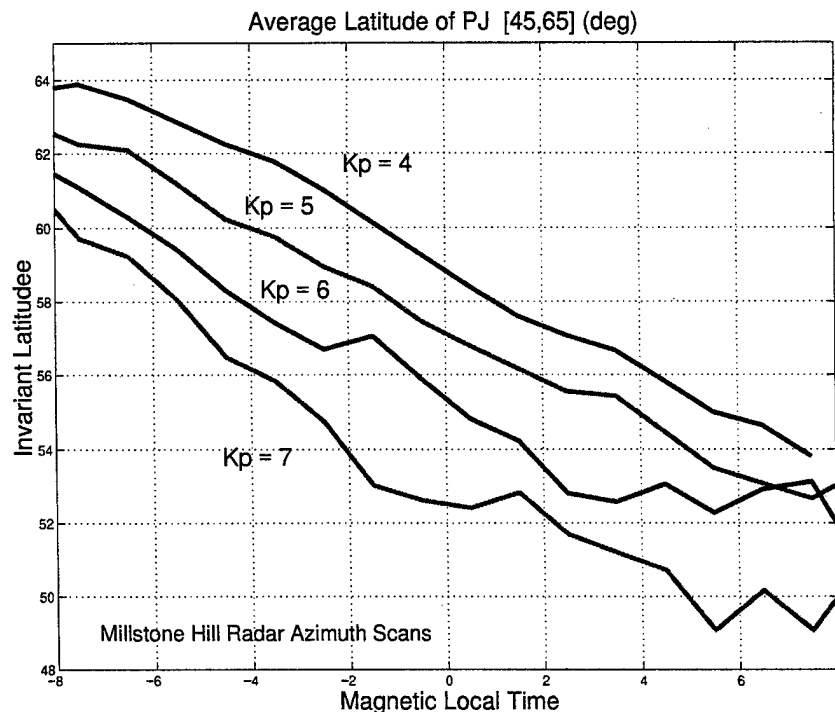

Figure 2. The average latitude of the peak of the polarization stream decreases uniformly as a function of both MLT and increasing Kp index. [*Foster and Vo*, 2002]

redistribution of thermal plasma within the coupled inner magnetosphere/ionosphere system. The overlap of the SAPS with the plasmasphere erodes its outer layers to form the steep disturbed-time plasmapause and spectacular plasmaspheric tails [*Foster et al.*, 2002]. As the polarization stream sweeps sunward, entrained plasmaspheric material is seen at ionospheric altitudes as plumes of storm enhanced density [*Foster*, 1993], and near the dayside magnetopause as plasmaspheric drainage plumes [*Su et al.*, 2001]. The SAPS convection channel carries storm enhanced density and patches of elevated total electron content (TEC) to mid and polar latitudes where associated density/TEC gradients and irregularities constitute significant space weather hazards [*Vo and Foster*, 2001].

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